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## Addressing Risk in the Acquisition Lifecycle With Enterprise Simulation

20 September 2013


**Dr. Douglas A. Bodner, Principal Research Engineer**

**Georgia Institute of Technology**




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Abstract

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**Keywords:** Enterprise simulation, risk, enterprise transformation, F-35 Joint Strike Fighter

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Doug Bodner is a principal research engineer in the Tennenbaum Institute at the Georgia Institute of Technology. His research focuses on computational analysis and decision support for design, operation, and transformation of enterprise systems. His work has spanned a number of industries, including automotive, electronics, energy, health care, military acquisition, paper and pulp, semiconductors, and telecommunications. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE) and the Institute of Industrial Engineers (IIE), and a member of the Institute for Operations Research and Management Science (INFORMS). He is a registered professional engineer in the State of Georgia.

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# Addressing Risk in the Acquisition Lifecycle With Enterprise Simulation

## Introduction

Defense acquisition is characterized by significant levels of risk throughout the lifecycle of new system development, production, and sustainment. Fundamentally, risk results from the combination of an uncertain future (probabilities) and its potential bad outcomes (magnitudes). Classic risk drivers in acquisition include immature technologies, overly optimistic baseline cost and schedule estimates, overly stringent requirements, poorly understood implicit requirements, and changing missions and environments. Increasingly, risks come from new sources, such as fiscal pressures on government spending and transformative initiatives in the acquisition enterprise.

This paper presents an enterprise simulation approach to analyzing risk in major acquisition programs. This approach models interactions between firms and agencies within the acquisition enterprise, and it also includes a decision/event network that is issued to characterize the relationships of risk drivers to outcomes. The approach is used to model the acquisition of the F-35 Joint Strike Fighter, a large-scale acquisition program that has seen effects from risk. The F-35 program embodies a number of transformative approaches to the defense acquisition enterprise. Such enterprise transformation efforts are prone to substantial risk. The focus is on the decision/event network and its use in characterizing risks. This program is currently in a combination of system design and development and low-rate initial production.

The remainder of this paper is organized as follows. The next section, Simulation of Acquisition Programs and Risk, describes the use of simulation in modeling and analyzing acquisition programs, with a focus on the uncertainties involved in such programs. Enterprise Simulation and Acquisition Risk Analysis introduces the methodology of enterprise simulation to study risks in acquisition programs. Then, the next two sections, F-35 Program Analysis and Risk Analysis and Mitigation, discuss the application of enterprise simulation to the F-35 program and analysis and mitigation of that program's risks. Finally, the last section, Conclusion, concludes and provides directions for future research.

## Simulation of Acquisition Programs and Risk

Computer simulation has traditionally been used to assess performance of acquisition and related processes. One such widespread use of simulation has

been in manufacturing, as a means of predicting such metrics as throughput and cost for a factory (Smith, 2003). Simulation enables the analysis of behavior and performance over time, taking into account probabilistic effects and risk (Law, 2007). Simulation can provide analysis under different factory configurations and operating scenarios, thus enabling possible factory designs, modifications or operating policies to be studied prior to adoption. Risk can be studied by identifying sources of risk and modeling their outcomes and probabilities for occurrence.

In recent years, simulation has seen application in a number of acquisition-related areas beyond production. These include system design and development (Bodner & Wade, 2013), software system development (Madachy, 2008), supply chain design and analysis (Kleijnen, 2005), and fleet sustainment (Smith, Searles, Thompson, & Cranwell, 2006). Other work has used simulation to study enterprise-level phenomena in acquisition (Bodner, Rahman, & Rouse, 2010; Wirthlin, 2009). These efforts have studied a variety of risk sources, including mis-allocation of resources, unplanned rework, changing mission profiles, changing demand patterns, and poorly designed processes.

The traditional use of simulation has been to study the technical aspects associated with acquisition program elements. These include work processes, testing, quality, schedules, part flows, inventory levels, bottlenecks, costs, and lead times. While this type of analysis is quite useful, it does not capture the socio-technical aspects of the enterprise, with its multi-actor collaborations, decision-making, public-private partnerships, and risks. For instance, firms that develop and manufacture complex products and systems employ an enterprise paradigm that involves large number of collaborating stakeholder firms (Bodner & Lee, 2012). This type of enterprise modeling has increasingly been incorporated in simulation (Barjis, 2011; Glazner, 2011).

Recently, two related types of simulation methods have come into usage that address socio-technical aspects of a system—agent-based simulation (Hillebrand & Stender, 1994; Saam & Schmidt, 2001) and organizational simulation (Nissen, 2007; Prietula, Carley, & Gasser, 1998; Rouse & Boff, 2005). Agent-based simulation focuses on the interaction of different agents in an eco-system. In an acquisition or enterprise context, agents can represent individuals or firms. One relevant example of its use is in modeling actor interactions in a supply chain (Albino, Carbonara, & Giannoccaro, 2007).

Organizational simulation seeks to model the behavior of people and firms in the context of a world model and organizational story. A world model represents the elements internal to the organization being modeled, as well as those relevant external elements. The organizational story represents a scenario being modeled. Organizational simulation has been used to model healthcare delivery, research &

development, and electronics design (Rouse & Bodner, 2009). In particular, research & development is characterized by high levels of risk, as new technologies under development often do not work out. This is similar to acquisition programs that involve development of new systems, as opposed to a new version of an existing system. Thus, one important use of simulation is to determine which enterprise-level and program-level decisions and criteria are best-suited to improved enterprise outcomes in a risky environment.

## Enterprise Simulation and Acquisition Risk Analysis

Recent work has extended the concept of organizational simulation to an enterprise simulation framework with an agent-based model for actors in an enterprise, a process-oriented model for phases and milestones in an enterprise, and a decision/event network to represent a risk-focused way of representing an organizational story (Bodner & Rouse, 2010). Actors represent organizations (e.g., firms or agencies) that participate in the enterprise. In an acquisition enterprise, they can perform a variety of actions, including

- communicate with other actors,
- react to incentives and information,
- accrue costs,
- change variables under their control, such as schedule targets or budgets,
- progress through processes and tasks,
- restructure a program, or
- terminate a program.

Figure 1 shows an example set of interactions in an acquisition context. The government program office interacts with the lead contractor, as well as with other agencies. The lead contractor manages the contractor network. Note that some contractors may be sub-contracted to multiple contractors. In a typical major program, of course, there are dozens of agencies, some outside the Department of Defense (DoD), and there are thousands of contractors organized in a multi-tier structure.

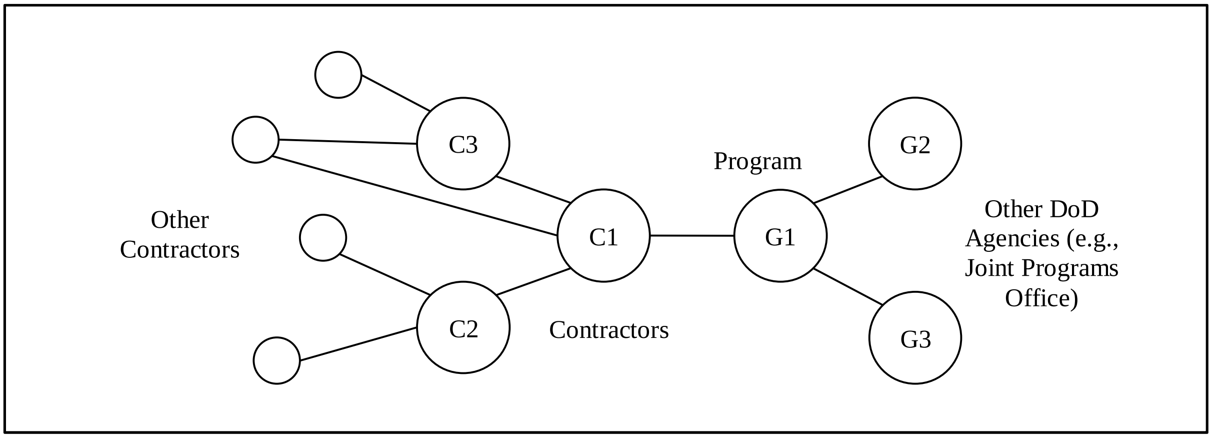


**Figure 1. Example Interactions of Agents as Firms or Agencies**

To provide a risk-focused organizational story, this framework utilizes a concept from interactive drama and artificial intelligence, that of a drama manager (Roberts & Isbell, 2008). Interactive drama is a narrative implemented in computational form, similar to a game, in which a user interacts with a story. The drama manager interacts with the story flow to give the story particular characteristics (e.g., simplicity versus complexity). It does this through a construct known as a plot point model, which abstracts important events in the plot of the story. A plot point model is organized as a directed acyclic graph of plot point nodes, some of which may have precedence relationships between them (i.e., arcs), and some of which may be mutually exclusive. A precedence relationship from node 1 to node 2 (i.e., node 1 precedes node 2, or 1→2) implies that for node 2 to occur, node 1 must occur. Given precedence relationships from multiple plot points to a particular plot point, only one of the predecessor plot points need occur to allow the successor plot point to occur (i.e., an "or" relationship among the precedence relationships). A precedence relationship can be mandatory in that the predecessor must occur for the successor node to occur (i.e., enabling "and" relationships).

The graph is acyclic to disallow two or more plot points from simultaneously having a cycle of precedence relationships among them. A terminal plot point represents an end to the story. The drama manager may influence the plot via actions so that certain events occur (or are more likely to occur), or it may likewise prevent certain events from occurring. The particular path of plot points realized in an interactive drama reflects the instantiated plot.

Adapted to a simulation context, the plot point model (or decision/event network) is used to represent important events in the simulation that relate, for example, to risk in the unfolding simulation. Thus, the role of a drama manager (or simulation manager) in the simulation context is to guide the simulation via actions through a particular set of decision/event nodes to reflect a certain risk profile. The

outcome of the simulation can then be compared to the risk profile chosen. Example simulation manager actions include the following:

- Direct selection of a node from among alternatives,
- Preference given to a particular node via probabilities, or
- Exclusion of a particular node.

Figure 2 illustrates the relationships among the simulation manager, the plot point model and the simulation. Certain events in the simulation model correspond to decisions or events in the decision/event network. However, the simulation contains many events and behaviors that are not critical to the organizational story and hence do not correspond to network nodes. Nodes 2 and 3 are mutually exclusive (only one at most may happen). Arcs 4→7 and 5→7 are mandatory precedence relationships, meaning that both nodes 4 and 5 must occur for 7 to occur. We also introduce the notion of both a trigger node and an associated inactive relationship. If a trigger node is activated, it in turn activates its associated relationship arc(s) (either a precedence arc or mutual exclusion arc). For example, in Figure 2, if node 2 occurs, it may trigger node A, which then activates a precedence relationship 2→4.

The decision/event network prescribes the relationships among decisions and events, not the outcome of a particular organizational story. An outcome is realized by a particular sequence of decisions and events. A valid sequence, or path, must conform to the precedence and exclusion constraints of the decision/event network, and it can have only one terminal node (at the path end). Nodes 6 and 7 are the two terminal nodes. A particular decision/event network can generate many different paths. An example valid path from Figure 2 is 1→2→6, as is 1→3→4→5→7. Note that Figure 2 does not specify valid paths, only precedence relationships. Thus, nodes 4 and 5 can occur in a valid path. In fact, both must occur for node 7 to occur.

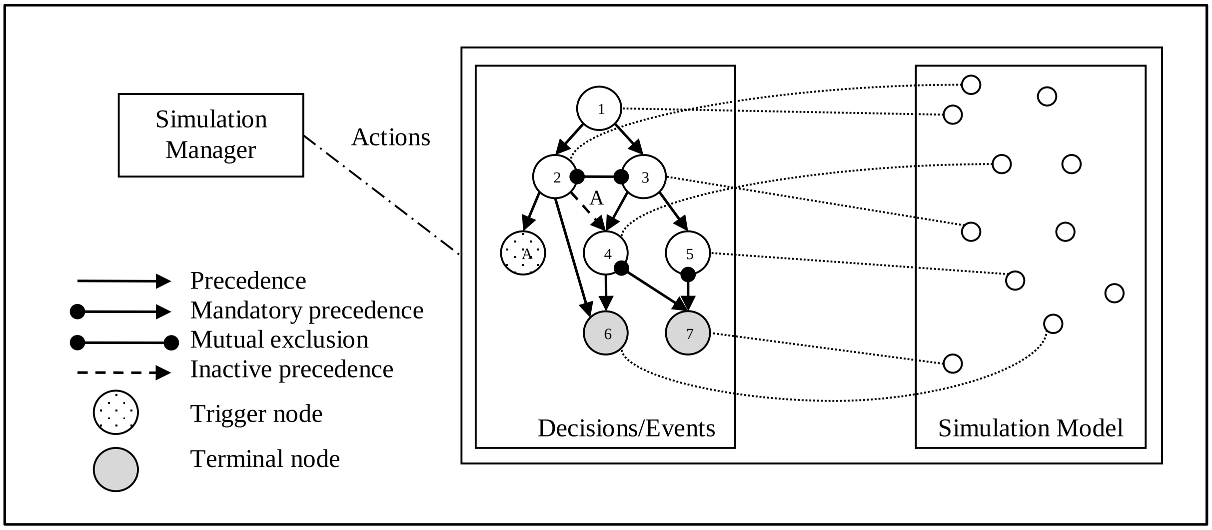


**Figure 2. Simulation and Decision/Event Network Interaction**

Given a particular decision/event network, the enterprise simulation framework conducts a pre-processing operation to determine the set of possible paths, and the result is returned in the form of a partial game tree. A game tree is a construct from game theory that defines moves that two players may make as alternating nodes in the tree. The simulation manager and simulation correspond to the two players in this context. Nodes in the decision/event network represent actions taken by the simulation (i.e., decisions and events). The simulation manager actions are not represented in a path, as these actions are intended to influence the path followed for a particular simulation outcome. Including the simulation manager's possible actions would make the full game tree representation unwieldy. Hence, the set of paths or simulation outcomes is a partial game tree. The partial game tree for the decision/event network from Figure 2 is shown in Figure 3. The trigger node A is not shown, since it does not represent an event or decision in the simulation other than to enable the 2→4 precedence relationship. An algorithm for generating a partial game tree from a decision/event network is provided in Bodner and Rouse (2010).

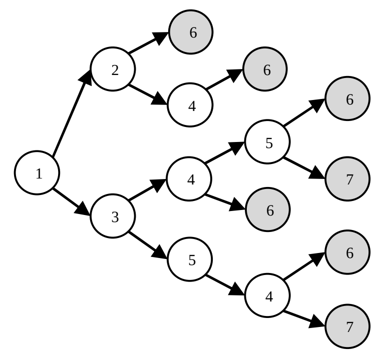


**Figure 3. Partial Game Tree From Decision/Event Network in Figure 2**

The simulation manager's actions are based on its search function and evaluation function. These functions are used to evaluate paths for selection of a next node in the partial game tree and a corresponding simulation manager action. For risk, the evaluation can use the expected value of a function of the program's schedule and cost outcomes for selection of the next node. This must be determined over the set of path remainders associated with each candidate's next node, where a path remainder is the set of nodes comprising the rest of a particular path given a current node location.

For example, assume that the simulation has executed the partial path 1→3→4 in Figure 3. Nodes 5 and 6 are the two candidates to execute next. The possible path remainders are 6, 5→6, and 5→7. The path with only node 6 is evaluated using simply the estimated schedule and cost values for node 6. Node 5 is evaluated using a function of the estimated schedule and cost values of the two other path remainders. The search function is responsible for searching through the partial game tree to identify paths and apply the evaluation function.

Of course, the simulation is stochastic, and the evaluation can only use estimates of schedules and costs. Another issue is the computational complexity associated with the evaluation over a large decision/event network. Thus, the look-ahead capability of a search function to analyze a path remainder can be limited to a certain number of nodes in the path. In this case, an estimate function must be provided for the last node to be considered that accounts for the paths that emanate from it.

The expectimax formulation (Michie, 1966) is one example of a search function with an evaluation function. Expectimax is a variant of minimax, which is a formulation used in two-player games, where the goal of one player (i.e., the simulation manager) is to seek the maximum benefit, while hedging against downside outcomes (both measured here according to the evaluation function).

Expectimax is of interest here because it specifically includes uncertainty associated with future outcomes of the simulation (and hence future organizational stories). Pure minimax assumes a rational opponent in game play. Expectimax, assuming use in a full game tree, is shown below in pseudo-code:

```
function expectimax(node, depth)
    if node is a terminal node or depth = 0
        return the heuristic value of node
    else if simulation manager is to play at node
        // Return value of maximum-valued child node
        let α := -∞
        foreach child of node
            α := max(α, expectimax(child, depth-1))
    else if simulation event at node
        // Return weighted average of all child nodes' values
        let α := 0
        foreach child of node
            α := α + (Probability[child] * expectimax(child, depth-1))
    return α
```

While the above function seeks to maximize, it can also be framed as a minimization function. Note that the search function is invoked only when the simulation manager is to select or influence selection of a next node in the partial game tree. However, it executes recursively using the full game tree that consists of simulation and simulation manager actions. Typically, at the simulation's turn in the recursion, it is assumed that all child nodes have equal probability of occurring, in the absence of other information. To address computational complexity, the depth of each search (i.e., look-ahead capability) may be bounded (i.e., the depth parameter in the pseudo-code).

The interaction of the simulation manager and the simulation is detailed below.

1. First, in a pre-processing step, the simulation manager constructs a partial game tree from the decision/event network. The decision/event network is modeler-specified. The partial game tree is stored.
2. The simulation manager evaluates each path in the partial game tree using the search and evaluation functions.
3. Starting at the root node, the simulation manager performs an action using results from the search and evaluation functions. This action may be to select one of the root node's children, or it may give preference to one child node, or it may exclude one or more child

nodes. If more than one node remains feasible after the simulation manager’s action, a probabilistic function is executed to select the next child node.

4. The simulation then is initiated to execute the selected node and its associated events and behavior not represented directly in the decision/event network. These events may also result in changes to node values for the evaluation function in the partial game tree in future iterations.
5. The simulation manager iteratively takes turns with the simulation as follows.
   a. The simulation manager marks the node in the partial game tree as having occurred and sets its pointer to this node in the partial game tree.
   b. The simulation manager invokes the search and evaluation functions on the children nodes of the current node.
   c. Based on results of the search and evaluation functions, the simulation manager performs an action that results in selection of one of the child nodes (similar to step 3 above).
   d. Control returns to the simulation. The simulation executes the selected node and its associated events and behavior (similar to step 4 above).
   e. If the selected node is a terminal node, control goes to step 6 below. Otherwise, it returns to step 5a above.
6. The simulation ends, and final statistics are computed.

The enterprise simulation modeling framework is implemented using AnyLogic™ with a set of Java class extensions for the agent models, the simulation manager, plot point models, and partial game trees. AnyLogic is a commercially available simulation product that supports multi-paradigm modeling using discrete-event, agent-based and system dynamics simulation.

## F-35 Program Application

One major acquisition program that is of interest with respect to risk analysis, and application of the enterprise simulation framework, is the F-35 Joint Strike Fighter (JSF) program. This section discusses the F-35 program as an application of risk analysis using enterprise simulation.

### F-35 Program Background

The F-35 program grew out of the need for a next generation tactical fighter fleet to replace the aging fleet of F-16s and F-18s. Due to the large size of these legacy fleets, the Joint Strike Fighter effort started as an ambitious, large-scale

concept. As the program became more defined, Boeing and Lockheed Martin Aeronautics led consortia that developed concept aircraft in a competition for the system design and development contract. When the Lockheed consortium won, the Joint Strike Fighter program entered into system design and development (SDD) in 2001. The initial planned procurement quantity was 2,852 planes.

The JSF actually consists of three variant aircraft (Gertler, 2012). The first (F-35A) is a conventional take-off and landing (CTOL) aircraft designed for the Air Force. The second (F-35B) is a short take-off and vertical landing (STOVL) aircraft designed for the Marines. The third (F-35C) is a carrier-suitable aircraft (CV) designed for the Navy.

The JSF program has used a transformative approach to acquisition of a major weapons system. In this context, transformation means a major change in the enterprise, moving from an as-is enterprise to a to-be enterprise, with specific intents (Kessler & Heath, 2006). The transformative elements of this approach include the following.

- Rather than the traditional command-and-control relationship between the lead contractor and its suppliers, the contract required a partnership model among three firms—Lockheed Martin Aeronautics, BAE Systems, and Northrop Grumman (Kessler, McGinnis, & Bennett, 2012).
- The program was planned as a global effort, whereby design, development, and production activities would occur globally across an international consortium of firms, rather than primarily at one single site. Countries with firms represented in the consortium would be partners, agreeing to purchase F-35s (Kapstein, 2004).
- Modeling and simulation technologies have been used extensively in SDD, essentially to provide a “testing in software” capability. The confidence in this testing approach enabled substantial concurrency to be designed into the program between development and production so that production started prior to the completion of flight testing (DoD, 2011). The level of concurrency was higher than similar programs.
- The program is developing three variants using a common platform targeting a high level of commonality of components across the three variants. The intent is to reduce cost (promote affordability) while providing aircraft to support three mission types. The three mission types require different high-level technical capabilities (stealth, STOVL, supersonic, and carrier capabilities) that historically have not been

combined to this degree in a single craft or platform (Blickstein et al., 2012).

- The production supply network was planned for use by sustainment (Kessler et al., 2012).

One of the first efforts in the SDD phase was to set up the global technology infrastructure needed to support the design of the F-35 among the different firms involved. This was a substantive and transformative initiative that required significant alignment among the enterprise leadership and major changes to processes among all stakeholder firms (Bodner et al., 2011). The technology requirements were challenging—providing real-time global access to the design database subject to myriad management and security constraints. The technical challenges turned out to be less difficult than the social and process changes needed. Overall, the set-up of the technology infrastructure was deemed successful.

Nevertheless, such major transformative elements entail risk (Rouse, 2006), and there have been a number of less-than-desirable outcomes (and potential future outcomes) for the program.

- A reduction in planned purchases of 400 occurred early in SDD, driving up unit costs (Blickstein et al., 2012).
- In the earlier part of SDD, there were weight and design issues that required significant additional effort to address (Blickstein et al., 2012).
- The weapons bay of the CV variant was redesigned for larger payload, resulting in the same redesign for the STOVL and CTOL variants. This redesign caused weight and stability problems for the STOVL (Blickstein et al., 2012).
- Due to schedule slippages and cost growth, the program was rebaselined in 2004 and 2007 (Blickstein et al., 2012).
- After DoD's Joint Estimating Team issued a report in late 2009 stating that the program would need an additional 30 months to complete SDD, the program was restructured (Government Accountability Office [GAO], 2011), adding 13 months to SDD schedule (as well as the needed funding), and withholding $614 million in award fees from the lead contractor. Three aircraft were also added to early production.
- In 2010, the program was found to have increased in cost over both the original baseline and the then-current baseline by enough that it was certified with a Nunn-McCurdy breach (Blickstein et al., 2012).

- Continued technical issues with the STOVL variant resulted in that part of the program being placed on a two-year “probation,” with its production schedule moved back (GAO, 2011).
- The U.S. government’s fiscal situation has called into question whether the planned quantities of aircraft will be purchased. Already the UK government has reduced its planned purchases (Gertler, 2012).

Blickstein et al. (2012) conducted a root cause analysis of the Nunn-McCurdy breach and identified the following underlying risk factors as root causes:

- SDD was designed around a concept demonstrator rather than around a prototype that would have accounted better for producibility. Harvey and Ryan (2012) found evidence that a prototype can reduce cost growth in procurement for fixed-wing aircraft.
- The engineering strategy focused on developing the CTOL variant first, rather than tackling the more difficult engineering design and development of the STOVL.
- The original baseline was overly optimistic on cost and schedule due to assumptions on component commonality and technology integration.

These in turn drove other issues that resulted in the eventual breach. Getting the high-level technical capabilities across the variants was more technically challenging than anticipated, involving extensive trade-offs. The initial weight problems caused redesign, and these design changes had to be distributed throughout the enterprise of collaborators. Due to the large number of suppliers, this process delayed test and production and hence drove up costs. Delays also resulted in work being done with higher labor rates.

The issue of concurrency has been raised as a cause of the program’s cost and schedule issues (DoD, 2011). Historical analysis has indicated that concurrency has not been a major cost and schedule risk driver (Congressional Budget Office [CBO], 1988). However, this type of analysis likely does not account for the complexity of the JSF program.

At present, the program is entering a fifth low-rate initial production (LRIP) increment that is a fixed-price contract with risk sharing between the government and contractor (Gertler, 2012).

## Decision/Event Network

The decision/event model for the model of the JSF SDD is shown below in Figure 4, and detailed descriptions for each node are provided in Table 1. At the top

of the figure are the major program design decisions modeled in this example. These include

- whether a prototype article is developed prior to full-scale development (i.e., beyond the concept demonstrator that was developed prior to SDD),
- whether the CTOL variant or the STOVL variant is given first design priority,
- whether the program engages in high concurrency or no concurrency, and
- whether the program engages in an alignment effort at the commencement of SDD.

These are risk drivers to be explored as the JSF program unfolds.

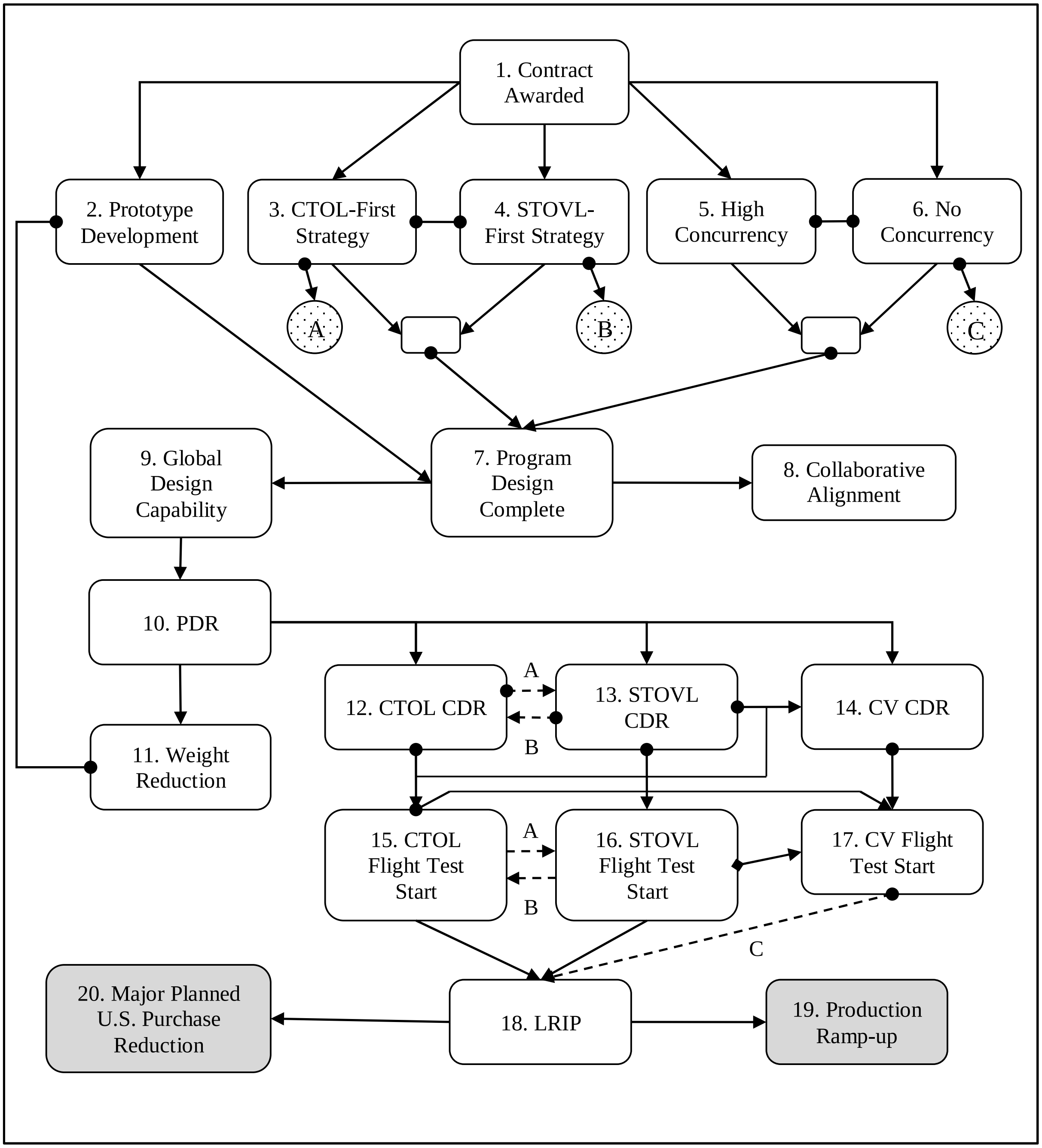


**Figure 4. JSF SDD Decision/Event Network**

If a prototype is developed, it is assumed that a weight reduction program later in development is not needed. Thus, nodes 2 and 11 are mutually exclusive. If a CTOL-first design and development strategy is adopted, then trigger node A causes the CDR for the CTOL variant to occur before that of the STOVL, as well as the flight test for the CTOL variant to occur before that of the STOVL. Similarly, if a STOVL-first design and development strategy is adopted, the converse occurs. There are two aggregating nodes without labels that are used to represent that one

of the CTOL or STOVL variant first design strategies must occur, as well as one of the concurrency alternatives.

After program design, the program must attain global design capability to enable collaborating firms to co-design the F-35. There may or may not be an effort by the leaderships of the top-tier partner firms to achieve alignment prior to this. After global design capability is achieved, preliminary design review (PDR) can occur, and then critical design review (CDR) and flight testing. Note that CDR and flight testing are separate for each variant. Also, it is assumed for this analysis that the CV variant undergoes both CDR and flight testing after the other two variants have done so. Thus, if the no-concurrency program design decision is made, inactive arc C is activated, causing LRIP not to occur before all flight testing is done.

The two terminal nodes represent either full-rate production at the planned level of production, or a 50% reduction that results from excessive cost growth, in an effort to reduce the overall program cost.

**Table 1. Decision-Event Descriptions**

| Decision-Event Node | Description |
|---|---|
| 1. Contract Awarded | SDD contract awarded to Lockheed Martin consortium. This initiates the organizational story. |
| 2. Prototype Development | This represents the program enterprise decision to develop or not develop a prototype aircraft in addition to the concept aircraft that won the SDD contract. Note that an affirmative decision delays PDR. |
| 3. CTOL-First Strategy | The program decides to design the CTOL variant first. |
| 4. STOVL-First Strategy | The program decides to design the STOVL variant first. Note that this is mutually exclusive with the CTOL-first strategy. |
| 5. High Concurrency | A high level of concurrency is designed into the program. |
| 6. No Concurrency | No concurrency is designed into the program. Note that this is mutually exclusive with the high concurrency decision. |
| 7. Program Design Complete | Program design is complete. |
| 8. Collaborative Alignment | The enterprise conducts an effort to achieve collaborative alignment on the changes needed to enable the global SDD technology infrastructure to be stood up. Achievement includes executive alignment among partner organizations, as well as technical management alignment. Achievement speeds up technology development over the case where there is little alignment. |
| 9. Global Design Capability | The enterprise achieves capability to support JSF design via global technology infrastructure. |
| 10. PDR | The program passes preliminary design review. |
| 11. Weight Reduction | The program engages in a major weight reduction effort. |
| 12. CTOL CDR | The CTOL variant passes critical design review. Note that |

| | |
|---|---|
| | CDR is a separate event for each variant. |
| 13. STOVL CDR | The STOVL variant passes critical design review. |
| 14. CV CDR | The CV variant passes critical design review. |
| 15. CTOL Flight Test Start | The CTOL variant starts flight testing. Once again, flight tests are modeled separately for each variant. |
| 16. STOVL Flight Test Start | The STOVL variant starts flight testing. |
| 17. CV Flight Test Start | The CV variant starts flight testing. |
| 18. LRIP | Low rate initial production begins. |
| 19. Production Ramp-up | Production ramp-up begins. This is a terminal decision/event. |
| 20. Major Planned U.S. Purchase Reduction | The U.S. decides to reduce its purchase quantity by 50%. |

A relatively simple agent interaction model is used to model the actors in the program. The program office, the lead contractor, and partner contractors are agents that interact in terms of cost accruals, program decisions, and program alignment.

## Baseline Model—Variables, Parameters, and Model Logic

The primary variables relate to schedule and cost. Supporting data is derived from the 2012 Selected Acquisition Report (SAR) for the F-35 (DoD, 2012). Cost variables are consistent with the 2012 SAR in that cost is divided into the categories of

- research, development, testing, and evaluation (RDT&E),
- procurement, and
- military construction.

The SAR further subdivides costs between the Navy (STOVL and CV variants) and the Air Force (CTOL variant) and also considers the aircraft costs separately from the engine costs, since the engine was categorized as a separate program. In the model, Navy and Air Force costs and the aircraft and engine costs are combined under the three main categories of RDT&E, procurement, and military construction. It should be noted that the RDT&E costs include non-Treasury funds (i.e., costs paid by partner countries in the F-35 program). In addition, base year 2012 dollars are used to track costs, providing a consistent unit of measure for the span of the program. It should be noted that the use of base year dollars has been criticized as a unit of measure because it understates actual out-year costs due to the effect of inflation. The main variables are as follows:

$T_i$ = occurrence time for node $i$ in the decision/event network (in months)

$R_t$ = cost accrual of RDT&E expenditures as of month *t* (in base year 2012 dollars)
$P_t$ = cost accrual of procurement expenditures as of month *t* (in base year 2012 dollars)
$U_t$ = estimated final unit cost as of month *t* (in base year 2012 dollars per aircraft unit)

Unit cost is computed as Program Acquisition Unit Cost (PAUC). PAUC considers RDT&E costs, procurement costs, and military construction costs in the overall program cost, which is then divided by the number of units to be made for both RDT&E (i.e., test articles) and procurement. This unit cost measure is used in preference to Average Procurement Unit Cost or fly-away cost, since PAUC considers RDT&E and military construction expenditures. This is especially relevant to a program such as the F-35 that is non-derivative of prior programs and thus has a substantial RDT&E cost component. PAUC not only includes those costs currently accrued, but also costs projected through the end of full rate production in 2037. Thus, in the simulation model, $U_t$ is computed via a look-ahead replication of the simulation starting at *t* and ending at production completion. This replication factors in the probability of full production (decision/event node 19) versus reduced purchase (decision/event node 20).

Cost accruals for RDT&E and procurement are assumed to occur at a rate dependent on the current phase of the program. These rates are parameters in the simulation model and are computed using cost data from the 2012 SAR (in base-year 2012 dollars). Tables 2 and 3 show the monthly spend rates for both RDT&E and procurement and the time periods from which they are derived using the SAR data. These are computed by converting the annual SAR data to monthly rates. In cases where the period spans only a partial year, the annual rate is pro-rated and then converted to monthly. For instance, an 18-month period spanning a full year and half of another would add the first year's cost plus half the second year's cost, then divide by the 18 months to obtain a monthly rate. In the simulation model, the rates are random variables uniformly distributed around the parameters in Tables 2 and 3 via the distributional form U(0.95*c*, 1.05*c*), where *c* is the cost rate in question.

Table 2. Spend Rates for RDT&E

| Program Phase | Rate | Period of Derivation |
|---|---|---|
| Initial accrual prior to SDD | $4,495M total | 1994–9/2001 |
| Up to PDR | $245.5M per month | 10/2001–4/2003 |
| PDR to CDR | $448.9M per month | 5/2003–6/2007 |
| Flight test—segment 1 | $380.6M per month | 7/2007–12/2008 |
| Flight test—segment 2 | $332.8M per month | 1/2009–6/2010 |
| Flight test—segment 3 | $141.7M per month | 7/2010–12/2018 |

Table 3. Spend Rates for Procurement

| Program Phase | Rate | Period of Derivation |
|---|---|---|
| Initial accrual prior to SDD | $0 total | 1994–9/2001 |
| LRIP preparation | $47.9M per month | 3/2006–3/2007 |
| LRIP | $597.7M per month | 4/2007–9/2018 |
| Full production (assuming all planned aircraft are produced) | $178,801.4M total | 10/2018–9/2037 |

Two additional parameters are the total amount of military construction expenditures *M* ($3,897.8 million) and the total number of aircraft that are planned for production (2,457, 14 of which are test planes produced via RDT&E).

The decision as to whether the program performs full rate production at the planned level or whether it reduces the buy by 50% is made probabilistically according to the following functions in Equations 1 and 2:

$$P(produce\ planned\ amount) = \begin{cases} 1\ if\ U_{T_{19}} < A \\ (B - U_{T_{19}})/(B - A)\ if\ A \leq U_{T_{19}} \leq B \\ 0\ if\ U_{T_{19}}\ if > B \end{cases} \quad (1)$$

$$P(reduce\ buy\ by\ 50\%) = 1 - P(produce\ planned\ amount) \quad (2)$$

Recall that $U_{T_{19}}$ is the projected unit cost (PAUC) at the end of LRIP, assuming that full rate production is to occur. Thus, if $U_{T_{19}}$ is less than a threshold *A*, then full rate production occurs. If it is over a threshold *B*, then the full buy does not occur. Otherwise, there is a probability that decreases linearly with $U_{T_{19}}$ whereby full rate production occurs. For the baseline model, A is set to $80 million, while B is set to $200 million. This corresponds to program costs of $196.6 billion and $491.4 billion, respectively, for the full purchase.

Of course, if the purchase amount is reduced by 50%, this dramatically affects the unit cost, since the fixed RDT&E and military construction costs must be amortized over a smaller number of units. Also, the procurement cost is not strictly linear, since efficiencies of increasing returns to scale are typically built into

projected production costs. Thus, one cannot simply reduce the procurement cost by half and obtain the procurement cost for 50% fewer planes.

In theory, these returns to scale are modeled by such approaches as a Cobb-Douglas production function (Cobb & Douglas, 1928), which uses an exponential function to relate inputs to outputs such as production quantity. Depending on the sign of the exponents, different returns to scale behaviors can be represented, including increasing, decreasing, or constant. However, the SAR data are not amenable to a statistical fit of such an exponential function using cost as input and production quantity as output. Thus, a piece-wise linear function was constructed by linear regression. Experimentation was performed to determine best cut-off points between a relatively small number of different linear segments, based on the best statistical fit. The results are shown in Table 4, where $Q$ is the production quantity, and $P$ is the procurement cost. Note that the production quantity funded by procurement is 2,443, whereas RDT&E is used to fund 14 additional aircraft. Also, these equations do not apply for small quantities of aircraft.

**Table 4. Regression Results for Production Function of F-35 Procurement**

| Quantity ($Q$) | Years | Production Equation | $R^2$ |
|---:|---|---|---|
| 0–179 | 2007–14 | $Q = -4.76 + 0.00455P$ | 0.999 |
| 180–559 | 2015–19 | $Q = -182 + 0.00836P$ | 0.994 |
| 560–1,960 | 2020–21 | $Q = -427 + 0.0110P$ | 1.000 |
| 1,961–2,443 | 2032–37 | $Q = -712 + 0.0123P$ | 1.000 |

If a purchase reduction is made, it reduces the total purchased from 2,443 to 1,221. This quantity falls into the third row of Table 4, with an input procurement cost of $P$ = $149,818.2M. The 14 aircraft purchased from RDT&E are included, then, in the total program quantity of 1,235 considered for the PAUC computation. The following two parameters are defined:

$u_{19}$ = production quantity for full production (node 19) = 2,457
$u_{20}$ = production quantity for reduced purchase (node 20) = 1,235

The initial month is set to the kick-off of the SDD, which is October of 2001. Thus, $t = 1$ refers to this month, and $T_1 = 1$ (i.e., contract award is defined to occur in the first month of the simulation).

## Validation

The baseline model is validated against current outcomes from the F-35 program by using the path in the decision/event network that corresponds to the existing program, as shown in Figure 6. Note that this assumes full production, as does the current program.

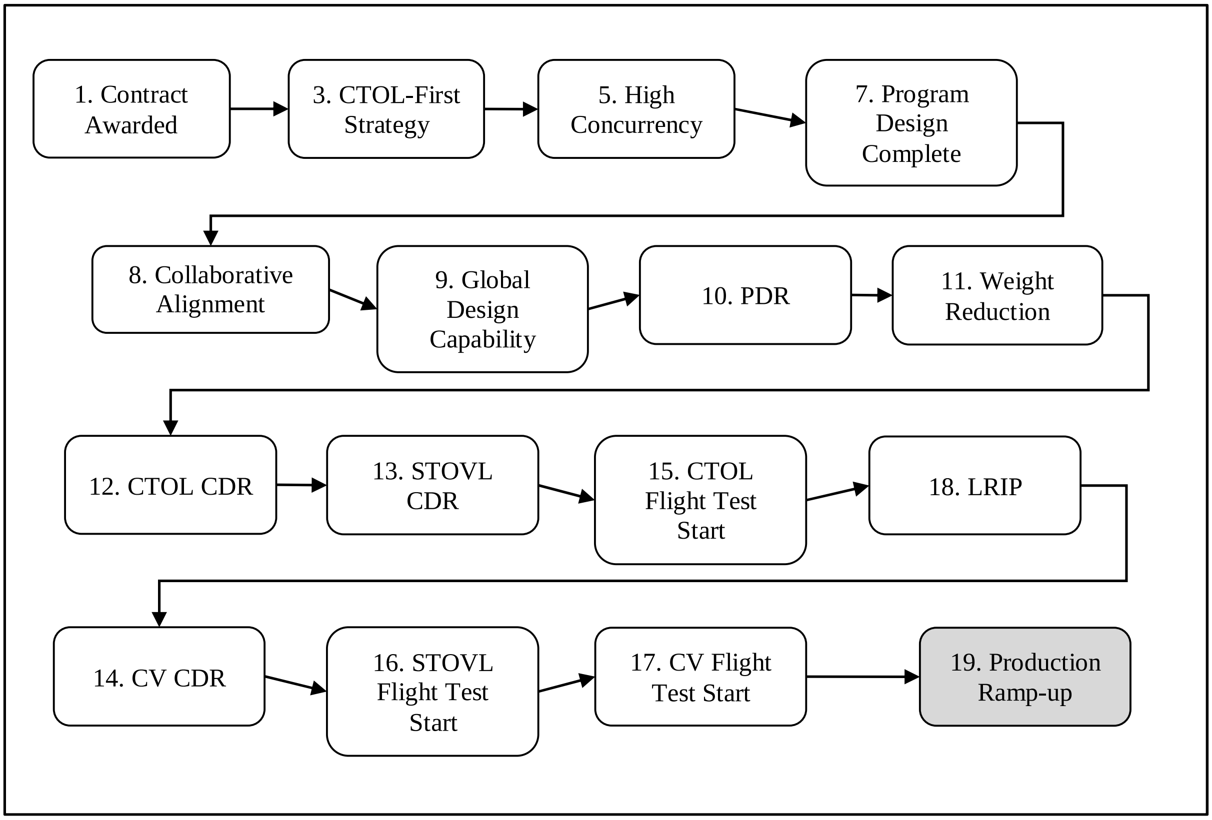


**Figure 5. Current JSF Program**

Comparisons from 25 simulation replications against outcomes from the existing JSF program are shown in Table 5. Existing program figures come from the 2012 SAR. It should be noted that these existing figures include projections from present until the expected initiation of full rate production in September 2018.

**Table 5. Validation**

| Outcome | Actual/Projected Program Outcome | 95% Confidence Interval From Simulation Outcomes |
|---|---|---|
| Expected schedule at initiation of FRP (months) | 204 (Sept 2018) | (202.5, 206.0) |
| RDT&E cost incurred at initiation of FRP (base year 2012 $) | $59,398.1M | ($58,317.7M, $59,450.4M) |
| Procurement cost at initiation of FRP (base year 2012 $) | $77,328.7M | ($81,602.3M, $83,647.4M) |
| Unit cost (PAUC, base year 2012 $ per unit) | $130.0M | ($131.0, 132.7M) |

The values from the baseline simulation are reasonably in line with the program outcome values. The schedule and the RDT&E costs incurred lie within their respective 95% confidence intervals. The other figures from the simulation are

biased upward slightly via parameters to account for a greater chance that the actual program outcomes will be higher rather than lower than the ones projected from the 2012 SAR. One primary reason is that the procurement cost is based on SAR data that includes a five-year projection of outcomes through 2018. The simulated outcome of unit cost is biased upward since it not only includes the projection of procurement costs through 2018, but also procurement costs through 2037 (the anticipated end of full rate production). RDT&E, on the other hand, is mostly expended by this point in the program, and final expenditures are more certain.

## Alternate Scenarios

The baseline simulation model is enhanced with additional scenarios for analysis, which include a possible prototype, a STOVL-first design strategy, a no-concurrency option, and the lack of an effort at alignment in preparation of global design. Altogether, 32 different paths are considered in the partial game tree, shown in Table 6. Path 17 refers to the baseline case. Path 18 assumes outcomes of the current program, with reduced purchase in the future.

**Table 6. Paths Considered in Partial Game Tree**

| | Prototype[1] | 1st Variant[2] | Concurrency[3] | Alignment[4] | Outcome[5] | Path (using nodes as defined in Table 1) |
|---|---|---|---|---|---|---|
| 1 | Y | C | H | Y | F | 1→2→3→5→7→8→9→10→12→13→14→15→18→16→17→19 |
| 2 | Y | C | H | Y | R | 1→2→3→5→7→8→9→10→12→13→14→15→18→16→17→20 |
| 3 | Y | C | H | N | F | 1→2→3→5→7→9→10→12→13→14→15→18→16→17→19 |
| 4 | Y | C | H | N | R | 1→2→3→5→7→9→10→12→13→14→15→18→16→17→20 |
| 5 | Y | C | N | Y | F | 1→2→3→6→7→8→9→10→12→13→14→15→16→17→18→19 |
| 6 | Y | C | N | Y | R | 1→2→3→6→7→8→9→10→12→13→14→15→16→17→18→20 |
| 7 | Y | C | N | N | F | 1→2→3→6→7→9→10→12→13→14→15→16→17→18→19 |
| 8 | Y | C | N | N | R | 1→2→3→6→7→9→10→12→13→14→15→16→17→18→20 |
| 9 | Y | S | H | Y | F | 1→2→4→5→7→8→9→10→13→12→14→16→18→15→17→19 |
| 10 | Y | S | H | Y | R | 1→2→4→5→7→8→9→10→13→12→14→16→18→15→17→20 |
| 11 | Y | S | H | N | F | 1→2→4→5→7→9→10→13→12→14→16→18→15→17→19 |
| 12 | Y | S | H | N | R | 1→2→4→5→7→9→10→13→12→14→16→18→15→17→20 |
| 13 | Y | S | N | Y | F | 1→2→4→6→7→8→9→10→13→12→14→16→15→17→18→19 |
| 14 | Y | S | N | Y | R | 1→2→4→6→7→8→9→10→13→12→14→16→15→17→18→20 |
| 15 | Y | S | N | N | F | 1→2→4→6→7→9→10→13→12→14→16→15→17→18→19 |
| 16 | Y | S | N | N | R | 1→2→4→6→7→9→10→13→12→14→16→15→17→18→20 |
| 17 | N | C | H | Y | F | 1→3→5→7→8→9→10→11→12→13→14→15→18→16→17→19 |
| 18 | N | C | H | Y | R | 1→3→5→7→8→9→10→11→12→13→14→15→18→16→17→20 |
| 19 | N | C | H | N | F | 1→3→5→7→9→10→11→12→13→14→15→18→16→17→19 |
| 20 | N | C | H | N | R | 1→3→5→7→9→10→11→12→13→14→15→18→16→17→20 |
| 21 | N | C | N | Y | F | 1→3→6→7→8→9→10→11→12→13→14→15→16→17→18→19 |
| 22 | N | C | N | Y | R | 1→3→6→7→8→9→10→11→12→13→14→15→16→17→18→20 |
| 23 | N | C | N | N | F | 1→3→6→7→9→10→11→12→13→14→15→16→17→18→19 |
| 24 | N | C | N | N | R | 1→3→6→7→9→10→11→12→13→14→15→16→17→18→20 |
| 25 | N | S | H | Y | F | 1→4→5→7→8→9→10→11→13→12→14→16→18→15→17→19 |
| 26 | N | S | H | Y | R | 1→4→5→7→8→9→10→11→13→12→14→16→18→15→17→20 |
| 27 | N | S | H | N | F | 1→4→5→7→9→10→11→13→12→14→16→18→15→17→19 |
| 28 | N | S | H | N | R | 1→4→5→7→9→10→11→13→12→14→16→18→15→17→20 |
| 29 | N | S | N | Y | F | 1→4→6→7→8→9→10→11→13→12→14→16→15→17→18→19 |
| 30 | N | S | N | Y | R | 1→4→6→7→8→9→10→11→13→12→14→16→15→17→18→20 |
| 31 | N | S | N | N | F | 1→4→6→7→9→10→11→13→12→14→16→15→17→18→19 |
| 32 | N | S | N | N | R | 1→4→6→7→9→10→11→13→12→14→16→15→17→18→20 |

[1] "Y" means prototype developed; "N" means no prototype.
[2] "C" means CTOL-first design; "S" means STOVL-first.
[3] "H" means high concurrency; "N" means no concurrency.
[4] "Y" means alignment sought; "N" means no alignment sought.
[5] "F" means full production of planned quantity; "R" means reduction of 50%.

## Risk Analysis and Mitigation

This section describes use of the simulation model to perform risk analysis. The simulation produces performance measures of unit cost (PAUC), schedule, RDT&E cost, and procurement cost. Unit cost is the primary performance measure chosen for analysis and is the decision criterion, since it is one of the prime

measures used to judge program success and program cost breaches. The other measures will be examined, as well.

## Risk Perspectives

Two different scenarios are studied, consisting of differing parameters. Within each case, three perspectives are examined. The first perspective is that of a risk-neutral decision-maker. A risk-neutral decision-maker is defined as one that would prefer to minimize the expected unit cost for the F-35 acquisition. The second perspective is that of a risk-averse decision-maker. A risk-averse decision-maker would like to minimize the maximum expected unit cost. The final perspective is that of a risk-seeking decision-maker. A risk-seeking decision-maker seeks to minimize the minimum expected unit cost.

The expectimax framework is used for the search and evaluation functions for each of these three perspectives. The objective is to minimize some function of unit cost. The search and evaluation functions operate as follows.

Let node *i* be a node in the partial game tree, and let $C_i$ be the set of child nodes of *i*. Let *i** be the number of the node in the decision/event network that corresponds to node *i*. Note that the partial game tree may contain multiple copies of each node in the decision/event network. The node index in the decision event network is used to reference simulation output variables to the corresponding node in the partial game tree.

Let $E(i)$ be the evaluation function for *i*. Let $S_i$ be the set of terminal nodes for the set of paths that emanate from *i*. For $j \in S_i$, $E(j)$ is defined as a function of the final projected unit cost at the time of node *j*.

$$E(j) = f\left(U_{T_{i*}}, j\right) \tag{3}$$

Note that the projected unit cost estimate is made at the time in the simulation of node *i*. Also, the function is dependent on the particular node *j*. In the F-35 example, for instance, the unit cost of the terminal node depends on whether there is full production or reduced purchase.

For *j* such that for all $k \in C_j$, $k \in S_i$, $E(j)$ is defined as the expected value of the unit cost over the child nodes weighted by the probabilities in Equations 1 and 2. For Equation 3, $p_{19}$ is given by Equation 1, and $p_{20}$ is given by Equation 2, where nodes 19 and 20 are the two terminal nodes.

$$E(j) = \sum_{k \in C_i} p_{k*} E(k) \tag{4}$$

For *j* such that for all $k \in C_j$, $k \notin S_i$, $E(j)$ is defined as the expected value of the unit cost averaged over the child nodes. Note that $E(i)$ can be computed with Equations 3 or 4.

$$E(j) = \sum_{k \in C_i} \frac{1}{|C_j|} E(k) \tag{5}$$

The search function is exhaustive, meaning that it examines each path emanating from *i* to its end. It does this by executing a simulation for each path starting at node *i* and terminating at the path's terminal node and using Equations 3 to 5 to provide an evaluation function for the children of node *i*. Note that the function form for $f\left(U_{T_{i*}}, j\right)$ depends on the risk perspective being utilized. For each case, the function utilizes the current RDT&E and procurement cost accruals ($R_{T_{i*}}$ and $P_{T_{i*}}$) as the starting point, and the projected function of final unit cost is computed by the simulation.

For the risk-neutral perspective, the functional form sums military construction, current cost accruals, and an average value for future cost accruals, namely $R_{exp}(T_{i*})$ and $P_{exp}(T_{i*})$, which are computed with a simulation replication using distributional averages of cost and schedule variables in the simulation. It then divides by the units produced at terminal node *j*.

$$f\left(U_{T_{i*}}, j\right) = \frac{M + R_{T_{i*}} + P_{T_{i*}} + R_{exp}(T_{i*}) + P_{exp}(T_{i*})}{u_{j*}} \tag{6}$$

Similarly, the risk-averse perspective substitutes $R_{max}(T_{i*})$ and $P_{max}(T_{i*})$ for the value of future cost accruals. These terms are computed using a simulation replication from using distributional maximums for cost and schedule variables. Finally, the risk-seeking perspective substitutes $R_{min}(T_{i*})$ and $P_{min}(T_{i*})$ for the value of future cost accruals. These terms are computed with a simulation replication using distributional minimums for cost and schedule variables.

For each perspective within each case, 100 replications of the simulation are made. The output results are then analyzed using Minitab 16.

## Scenario 1

For the different risk perspectives in the first scenario, the following assumptions are made and parameters adopted using the baseline model as a starting point.

- For the case of no alignment sought, the attainment of global design capability is pushed back by three months.
- For the case of no concurrency, LRIP commences after flight testing begins for the CV variant by a period of months triangularly distributed ~TR(16, 21, 18). In this notation, the first parameter is the minimum, the second the maximum and the third the mode. The triangular distribution is used often in simulation when there is little information

on an exact distributional form. LRIP lasts for a period of months distributed ~TR(60, 75, 68) months. However, LRIP is given a 75% increase in procurement cost rate due to the focused effort in a shortened timeframe separate from design.

- For the STOVL-first design case, the STOVL CDR occurs after the CTOL CDR design would have occurred by a period of months distributed ~TR(6, 9, 27), allowing additional time for the more complex requirements for the STOVL. However, the flight testing begins twelve months sooner.
- For the prototype development case, PDR is pushed back an amount of time distributed ~TR(20,36,24), and the PDR cost rate is increased by 50% to reflect the prototype development cost. Both CDR and full rate production are pushed forward by a period of months distributed ~TR(9,18,15), reflecting efficiencies gained by knowledge from the prototype. Finally, the procurement cost rate is decreased by 10% to allow for knowledge gained by the prototype, as an estimate reflecting results from Harvey and Ryan (2012) indicating that procurement costs can be reduced by a prototype.
- For the case of prototype development and no concurrency, full-rate production is pushed forward by a period of months distributed ~TR(3, 10, 8) instead of ~TR(9,18,15), reflecting increased schedule needed for no concurrency.

Summary performance statistics from the 100 simulation replications for the three perspectives are shown below in Table 7. The column with heading "Full Production" denotes the percentage of simulation outputs that result in full production versus reduced purchase.

**Table 7. Average Simulation Results for Each Perspective in Scenario 1**

| Case | Unit Cost | Schedule | RDT&E Cost | Proc. Cost | Full Production |
|---|---|---|---|---|---|
| Risk-neutral | $132.4M | 188.9 mos. | $65,070.5M | $199,239.4M | 69% |
| Risk-averse | $130.4M | 186.8 mos. | $63,690.7M | $201,812.6M | 73% |
| Risk-seeking | $130.8M | 189.7 mos. | $65,258.7M | $202,934.9M | 74% |

The unit costs are not statistically different across the three perspectives. There is moderate evidence that the schedule in the risk-seeking perspective differs from that in the risk-averse perspective (with $p = 0.065$). For RDT&E costs, however, the cost from the risk-averse perspective turned out to be statistically different from that of the others. For it and the risk-averse perspective, $p = 0.026$, while for it and the risk-seeking perspective, $p = 0.012$. The procurement costs are

not statistically different among the three perspectives. There is not a statistically significant difference among the percentages of replications at which full production is achieved among the three perspectives. In conclusion, for the set of parameters in this particular scenario, there is little observable difference in outcomes among the three different risk perspectives. This suggests that the three perspectives, for the set of parameters operating in this scenario, select path outcomes that generate relatively similar performance outcomes.

More interesting, though, is the distribution of paths through the program lifecycle produced by each of the three alternative perspectives. These are summarized in Table 8. Note that a path pair is shown here for each entry in the path distribution. The path pair consists of the two paths with the same set of program design decisions, but different outcomes relative to purchase reduction versus full production. For instance, paths 13 and 14 have the same set of design decisions (prototype development, STOVL-first design strategy, no concurrency, and program partner alignment sought immediately after contract win). However, path 13 has full production, while 14 has reduced purchase. We assume that the risk perspective selection of paths relates to the program design decisions, and not to the production level outcome, which is dependent on the customer (i.e., government) via probabilities. The percentage of full production outcomes for each set of program decisions made under each risk perspective is shown in column 4.

**Table 8. Paths Generated by Different Perspectives for Scenario 1**

| Perspective | Path Pair | Frequency | Full Production % |
|---|---|---:|---:|
| Risk-neutral | 13/14 | 65% | 64.6% |
| | 15/16 | 33% | 75.8% |
| | 9/10 | 2% | 0% |
| Risk-averse | 13/14 | 54% | 74.1% |
| | 5/6 | 30% | 76.7% |
| | 15/16 | 14% | 64.3% |
| | 7/8 | 2% | 0% |
| Risk-seeking | 13/14 | 69% | 76.8% |
| | 15/16 | 28% | 67.9% |
| | 9/10 | 3% | 66.7% |

All perspectives prefer development of a prototype. The majority of selections include the STOVL-first design strategy (except for the 32% of the risk-averse perspective's selections that consist of paths 7/8 and 5/6). The vast majority of selections include no concurrency. The exceptions are paths 9/10 chosen by the risk-neutral and risk-seeking perspectives. The majority of paths selected include the alignment effort at the beginning of SDD. However, a significant fraction do not

(7/8 and 15/16), indicating that this effort tends to have less effect on cost reduction than the other design decisions and is often overcome by the randomness in outcomes from the simulation's probabilistic nature.

The path selection outcome distribution generated from the risk-averse perspective seems quite different from that of the other two perspectives. This is confirmed using a chi-squared test of independence of categorical variables. The risk-averse perspective is different from both other perspectives, with $p = 0.000$ in each case. However, the evidence did not support the conclusion that the risk-neutral and risk-seeking perspectives had statistically different outcomes.

The risk-averse perspective selected the CTOL-first design strategy for a significant fraction of its paths, indicating that the STOVL-first design strategy likely has a probabilistic risk of higher cost that contributes to a greater maximum expected unit cost. The prototype option and the no-concurrency option seem not to have this issue (i.e., they are net positives to unit cost in terms of the expected value, minimum expected value, and maximum expected value).

### Scenario 2

In Scenario 1, the prototype alternative is quite attractive, since it pushes back PDR (increasing schedule with a relatively low burn rate), while pushing up CDR and production (decreasing schedule with a relatively high burn rate). In Scenario 2, the prototype development alternative is made less attractive in terms of schedule for the program.

In the case of the prototype relative to the baseline without it, CDR and production are pushed forward a period of months triangularly distributed ~TR(-9, 12, 3). This means that there is a risk that the prototype may actually delay CDR and production. Similarly, for the case of the prototype and no concurrency, production is pushed forward months distributed ~TR(-15, 4, -4) rather than ~TR(-9, 12, 3). Thus, production is expected to be pushed back relative to the baseline here.

**Table 9. Average Simulation Results for Each Perspective in Scenario 2**

| Perspective | Unit Cost | Schedule | RDT&E Cost | Proc. Cost | Full Production |
|---|---|---|---|---|---|
| Risk-neutral | $139.2M | 195.6 mos. | $63,827.7M | $211,117.5M | 68% |
| Risk-averse | $133.8M | 187.5 mos. | $60,096.7M | $218,806.7M | 76% |
| Risk-seeking | $144.1M | 214.6 mos. | $72,278.9M | $201,483.9M | 62% |

In this scenario, there are significant differences among the outcome measures from the three different perspectives. The unit costs of the risk-averse and risk-seeking perspectives show significant difference with $p = 0.001$. There is moderate evidence that the unit cost of the risk-neutral perspective differs from the

other two, with *p* values of 0.081 (from risk-averse) and 0.130 (risk-seeking) respectively. The schedule outcomes and RDT&E cost outcomes differed among all three perspectives with $p = 0.000$ for each pair-wise comparison. Finally, the procurement costs showed significant difference between the risk-averse perspective and the risk-seeking perspectives ($p = 0.005$). There was moderate evidence of differences between other pairs of procurement costs, with $p = 0.185$ for risk-neutral and risk-averse and $p = 0.130$ for risk-neutral and risk-seeking.

One key difference between this scenario and the previous is the difference in the percentage of outcomes that achieve full production among the perspectives. Clearly, the risk-seeking perspective achieves a lower percentage of full production outcomes than the other two. The difference between it and the risk-averse perspective's full production outcome is significant at $p = 0.03$. However, there is not sufficient evidence to indicate a true difference between the risk-neutral outcome and the other two. It is the lower full production outcome for the risk-seeking perspective that is causing a decrease in its procurement cost, due to fewer units being produced on average, as well as an increased unit cost, due to having to amortize RDT&E and procurement costs over fewer units. This is especially the case since RDT&E costs for the risk-seeking perspective is substantially larger than for the other two perspectives.

Once again, the different perspectives yield differing distributions of paths selected. These are shown below in Table 10.

**Table 10. Paths Generated by Different Perspectives for Scenario 2**

| Perspective | Path Pair | Frequency | Full Production % |
|---|---|---|---|
| Risk-neutral | 21/22 | 31% | 64.5% |
| | 29/30 | 31% | 67.7% |
| | 31/32 | 20% | 90.0% |
| | 23/24 | 17% | 47.1% |
| | 25/26 | 1% | 100.0% |
| Risk-averse | 21/22 | 60% | 81.7% |
| | 23/24 | 40% | 67.5% |
| Risk-seeking | 13/14 | 58% | 60.3% |
| | 15/16 | 30% | 63.3% |
| | 9/10 | 12% | 80.0% |

Clearly, the risk-seeking perspective yields a much different distribution of outcomes paths than do the other two perspectives. Also, the risk-neutral perspective seems to yield different path results than the risk-averse perspective. From a statistical point of view, however, the chi-squared test of independence is valid only for the comparison of the risk-averse and risk-seeking perspectives, where

it provides strong evidence of a difference in outcomes with *p* = 0.000. It is not valid for the other two comparisons due to numerical issues. It will be assumed, though, that the other two comparisons, in fact, yield different results, and that all three perspectives have differing path outcome distributions.

In this scenario, only the risk-seeking alternative chooses to execute a prototype development, and this is done in 100% of cases. It also chooses the STOVL-first design strategy in 100% of cases. In fact, its path outcome distribution appears similar to the distribution of the risk-seeking perspective in Scenario 1 (Table 8). However, the chi-squared test of independence of categorical variables is used to show that, despite the same set of outcome paths, the proportions of path outcomes are different enough to declare that the distributions are different at *p* = 0.04. Thus, in Scenario 2, the conclusion is that high-concurrency is somewhat more favored by the risk-seeking perspective than in Scenario 1, due to the higher proportion of path pair 9/10.

The risk-averse perspective chooses no prototype, CTOL-first design strategy, and no concurrency. Similar to Scenario 1, the alignment effort alternative is preferred (with 60% of outcomes), but its effectiveness at cost reduction seems to be marginalized by the effect of randomness in the simulation.

The risk-neutral perspective augments the risk-averse perspective’s selections with a variety of path pairs, all of which include the STOVL-first design strategy and one of which contains high concurrency (25/26), although at only one occurrence.

Overall, several conclusions can be drawn from Scenario 2 for the set of parameters studied:

- Use of a prototype is a risk-upside strategy associated with risk-seeking, as is STOVL-first design strategy.
- Similar to Scenario 1, the alignment effort produces too little cost savings in RDT&E to offset much of the simulation randomness.
- Risk-seeking with this set of parameters resulted in higher rates of purchase reduction, which drives lower procurement costs, but also higher unit costs. So risk-seeking is not an attractive strategy in this scenario.

## Discussion

The two scenarios analyzed here present different risks in the program design decisions of interest for the F-35 program. These risks are studied from the perspectives of a risk-neutral decision-maker, a risk-averse decision-maker and a risk-seeking decision-maker. In Scenario 1, most of the risk of changing program

design decisions from those made in the actual program is to the upside. That is, they tend to improve the unit cost outcome over the span of probabilistic outcomes. The three perspectives, therefore, have very similar performance outcomes. In addition, their path selection outcomes are not drastically different. Thus, it can be concluded for the most part that changing design decisions to prototype development, STOVL-first design, and no concurrency yields superior results.

On the other hand, Scenario 2 presents a more balanced set of risks if design decisions are changed. The different risk perspectives differ substantially in their performance outcomes and path selections. This demonstrates the capability of the enterprise simulation methodology to analyze a program or enterprise based on different risk perspectives, so that the decision-maker can select the one that best matches his or her perspective, while understanding outcomes based on other perspectives.

It should be noted that the alignment effort tends to have a positive effect on unit costs in both scenarios. However, it is often masked by the probabilistic nature of simulation outcomes, since its effect is not large. However, a failure or significant delay in attaining global design capability could have political or organizational costs that are not modeled here. This is an avenue of further research.

Finally, the parameters used in both scenarios reflect estimates of what the actual effects would be from changing design decisions. A rigorous use of sensitivity analysis should be conducted in the future to generate a set of response surfaces to characterize the conditions under which certain design decisions are superior to others under different risk perspectives.

## Conclusions and Future Research

This report has presented an enterprise simulation framework and methodology for studying risks in defense acquisition programs. The main focus is the use of a decision/event network as an organizational story to characterize risk drivers and outcomes, as well as to support simulation analysis of the risks and risk-related outcomes. This is a novel use of simulation, which tends to focus mostly on experimental analysis or what-if analysis for such systems as acquisition.

In particular, the enterprise simulation methodology allows studying risks from different risk perspectives. This methodology is applied to a case study involving acquisition of the F-35 Joint Strike Fighter. The F-35 program is the largest military acquisition program in history, and it has generated risks and adverse outcomes, in part due to its scale, complexity, and transformative approach to acquisition. Simulation analysis is used to study the preferred outcomes of three different risk perspectives on two different scenarios. It is shown that the risk perspectives can be

used to identify when a particular scenario has a mostly upside set of risks, in which case the perspectives tend to agree on preferred organizational stories and performance outcomes, and also when a scenario has a mixture of upside and downside risks. Similarly, it can be inferred that a scenario with mostly downside risks can be identified in this manner. Such analysis is especially important in transformation efforts, where many risks are present and may interact.

Two additional benefits of this methodology are the following:

- For a complex scenario with many different possible decisions and events, this methodology can be used to identify promising paths through the decision/event network, thus avoiding analysis over the whole state space.
- A decision-maker can view the scenario through his or her preferred risk perspective to determine which outcomes are preferred.

There are a number of future research avenues that can be pursued, both for the enterprise simulation methodology and its application to the F-35 program. In terms of the methodology, future research includes the following:

- The number of nodes and complexity of the network should be scaled up to allow analysis of computational issues. Computational methods can then be developed to ameliorate the effect of large state spaces.
- The current methodology uses only one performance measure in the evaluation function. This could easily be extended to a weighted function of two or more performance measures. It would also be of interest to use other multi-criteria decision approaches such as Pareto optimality or minimization of deviance from multiple performance goals.
- The methodology could be made interactive, with a person as the decision-maker relying on their interpretation of evaluation functions.

In terms of the F-35 program analysis, future research includes the following:

- Additional socio factors could be included beyond alignment, such as the political and organizational cost of certain decisions.
- The procurement cost data from the SAR is assumed to be accurate for the program's out-years. Analysis could be done to determine the effect of increases or decreases in these projected figures.
- Different probabilities for program purchase reduction could be analyzed to determine their effect on the different risk perspectives.

- Likewise, a more complex set of adverse outcomes that just a 50% purchase reduction could be studied (e.g., a range of percentages for the reduction or even a cancellation alternative).
- The analysis could be extended to sustainment, which is expected to consume major funding once the fleet starts to come online.

## References


Albino, V., Carbonara, N., & Giannoccaro, I. (2007). Supply chain cooperation in industrial districts: A simulation analysis. *European Journal of Operational Research, 177*, 261–280.

Barjis, J. (2011). Enterprise modeling and simulation within enterprise engineering. *Journal of Enterprise Transformation, 1*(3), 185–207.

Blickstein, I., Boito, M., Drezner, J., Dryden, J., Horn, K., Kallimani, J. G., … Wong, C. (2011). *Root cause analyses of Nunn-McCurdy breaches, vol. 1* (MG-1171/1-OSD). Santa Monica, CA: RAND.

Bodner, D. A. (2012). Addressing risk in the acquisition lifecycle with enterprise simulation. In *Proceedings of the Ninth Annual Acquisition Research Symposium* (Vol. I, pp. 74–87). Monterey, CA: Naval Postgraduate School.

Bodner, D. A., & Lee, I.-H. (2012). Organizational simulation in support of global manufacturing enterprises. *Information, Knowledge, Systems Management, 11*(1–2), 101–117.

Bodner, D. A., Medvidovic, N., Lane, J. A., Boehm, B. W., Kessler, W. C., Rouse, W. B., … Popescu, D. (2011). *Requirements management for net-centric enterprises—Final report* (Technical report SERC-2011-TR-021). Hoboken, NJ: Stevens Institute of Technology, Systems Engineering Research Center.

Bodner, D. A., Rahman, F., & Rouse, W. B. (2010). Addressing cost increases in evolutionary acquisition. In *Proceedings of the Seventh Annual Acquisition Research Symposium* (Vol. 1, 329–345). Monterey, CA: Naval Postgraduate School.

Bodner, D. A., & Rouse, W. B. (2010). *Final report for "A Framework and Tools for Organizational Simulation"* [Technical report]. Atlanta, GA: Georgia Institute of Technology, Tennenbaum Institute.

Bodner, D. A., & Wade, J. P. (2013). Multi-criteria simulation of program outcomes. In *Proceedings of the 2013 IEEE International Systems Conference* (pp. 215–221). Piscataway, NJ: IEEE.

Cobb, C. W., & Douglas, P. H. (1928). A theory of production [Supplement]. *American Economic Review*, *18*, 139–165.

Congressional Budget Office (CBO). (1988). *Concurrent weapons development and production*. Washington, DC: Author.

Department of Defense (DoD). (2011). *F-35 Joint Strike Fighter concurrency quick look review*. Washington, DC: Author.

Department of Defense (DoD). (2012). *Selected acquisition report (SAR): F-35 Joint Strike Fighter Aircraft (F-35)*. Washington, DC: Author.

Ford, D. N., & Dillard, J. (2009, July). Modeling the performance and risks of evolutionary acquisition. *Defense Acquisition Review Journal*, 143–158.

Gertler, J. (2012). *F-35 Joint Strike Fighter (JSF) program*. Washington, DC: Congressional Research Service.

Glazner, C. (2011). Enterprise transformation using a simulation of enterprise architecture. *Journal of Enterprise Transformation, 1*(3), 231–260.

Government Accountability Office (GAO). (2011). *Joint Strike Fighter: Restructuring places program on firmer footing, but progress is still lagging* (GAO-11-677T). Washington, DC: Author.

Harvey, W. B., & Ryan, C. M. (2012). *A quantitative analysis of the benefits of prototyping fixed-wing aircraft* (Master's project report). Dayton, OH: Air Force Institute of Technology.

Hillebrand, E., & Stender, J. (1994). *Many-agent simulation and artificial life*. Amsterdam, The Netherlands: IOS Press.

Kapstein, E. B. (2004). Capturing Fortress Europe: International collaboration and the Joint Strike Fighter. *Survival, 46*(3), 137–160.

Kessler, W. C., & Heath, R. D. (2006). Lockheed Martin Aeronautics: Restructure and transformation. In W. B. Rouse (Ed.), *Enterprise transformation: Understanding and enabling fundamental change* (pp. 431–464). Hoboken, NJ: Wiley-Interscience.

Kessler, W. C., McGinnis, L. F., & Bennett, N. (Eds.). (2012). *Enterprise transformation: Manufacturing in a global enterprise*. Amsterdam, The Netherlands: IOS Press.

Kleijnen, J. P. C. (2005). Supply chain simulation tools and techniques: A survey. *International Journal of Simulation and Process Modelling, 1*(1–2), 82–89.

Law, A. M. (2007). *Simulation modeling and analysis*. Boston, MA: McGraw-Hill.

Madachy, R. (2008). *Software process dynamics*. Washington, DC: Wiley-IEEE Press.

Michie, D. (1966). Game-playing and game-learning automata. In L. Fox (Ed.), *Advances in programming and non-numerical computation* (pp. 183–200). Oxford, England: Pergamon Press.

Nissen, M. E. (2007). Computational experimentation on new organizational forms: Exploring behavior and performance of edge organizations. *Computational and Mathematical Organization Theory, 13*(3), 203–240.

Prietula, M., Carley, K., & Gasser, L. (Eds.). (1998). *Simulating organizations: Computational models of institutions and groups*. Menlo Park, CA: AAAI Press.

Roberts, D. L., & Isbell, C. L. (2008). A survey and qualitative analysis of recent advances in drama management. *International Transactions on Systems Science and Applications, 4*(2), 61–75.

Rouse, W. B. (Ed.). (2006). *Enterprise transformation: Understanding and enabling fundamental change.* Hoboken, NJ: Wiley-Interscience.

Rouse, W. B., & Bodner, D. A. (2009). Organizational simulation. In A. P. Sage & W. B. Rouse (Eds.), *The handbook of systems engineering and management* (2nd ed., pp. 763–792). New York, NY: John Wiley & Sons.

Rouse, W. B., & Boff, K. R. (Eds.). (2005). *Organizational simulation: From modeling & simulation to games & entertainment.* New York, NY: Wiley.

Saam, N. J., & Schmidt, B. (Eds.). (2001). *Cooperative agents: Applications in the social sciences*. New York, NY: Springer.

Smith, J. S. (2003). Survey on the use of simulation for manufacturing system design and operation. *Journal of Manufacturing Systems, 22*(2), 157–171.

Smith, V. D., Searles, D. G., Thompson, B. M., & Cranwell, R. M. (2006). SEM: Enterprise modeling of JSF global sustainment. In L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nicol, & R. M. Fujimoto (Eds.), *Proceedings of the 2006 Winter Simulation Conference* (pp. 1324–1331). Piscataway, NJ: IEEE.

Wirthlin, J. R. (2009). *Identifying enterprise leverage points in defense acquisition program performance* (Doctoral dissertation). Cambridge, MA: Massachusetts Institute of Technology.

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